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INFLUENCE OF DESIGN ON COST OF OPERATING AIRPLANES.

By Archibald Black.

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INFLUENCE OF DESIGN ON COST OF OPERATING AIRPLANES.

By Archibald Black.*

The author discusses cost of operating commercial airplanes and endeavors to clear up prevalent misunderstandings. Curves of operating cost for varying duration, speed, reserve horsepower, etc., are developed. Calculations are made to illustrate the impracticability of requiring twin-engined commercial airplanes to fly on one engine, and initial rate of climb of 400 to 500 feet in the first minute is proposed as the standard of safe performance. Air Mail Service costs are used to show that airplanes designed for commercial use and fully loaded can be operated at a total cost of from 0.030 to 0.032 cent per pound-mile or 3.5 cents per passenger-mile, exclusive of the cost of obtaining the business.

This paper has been prepared with the intention of exploding certain widely held fallacies regarding the performance for which commercial airplanes should be designed. It presents the results of a study of the relation between designed performance and unit operating cost for such airplanes. The data were compiled by the former firm of A.&D. R. Black on work for its clients, and should be regarded as forming a qualitative rather than a quantitative analysis. That is, the data given, while capable of general application to all types, will be slightly modified in the case of machines radically different from the conventional type considered.

The most generally held erroneous ideas regarding commercial airplanes are probably the following: (1) That duration of flight of eight or even ten hours is practicable; (2) that speeds of 125 to 130 m.p.h. or more are practicable; (3) that a twin-engined machine should be capable of flying with one engine run-

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ning; (4) that a factor of safety of eight or more is desirable; (5) that comparatively high climbing ability is necessary and practicable; and (6) that very large airplanes are the most suitable for commercial use. While such notions are most common among those without experience in the design or operation of airplanes, they have sometimes been advanced by others who have less excuse. Probably this misunderstanding is due to the frequent practice of using for commercial work machines not suited to this purpose.

The presumption is made here that commercial airplanes are designed primarily for operation at a profit, so that operating cost and safety become the most vital considerations. When this work was started it was found possible to eliminate some duplication by basing many of the calculations upon a British report on the division of total weight of different airplanes.* Fig. 1 is reproduced from this report with data on weights and horsepower added.

Weight Division vs. Size, Duration, and Speed.

As a preliminary to consideration of the variation of unit operating cost with size, duration, speed, etc., it becomes necessary to study the variation of net pay load with these elements. Figs. 1 to 6 should be regarded merely as furnishing the data necessary for later curves and may be passed over with little comment. They are included here because of their value for reference. Each figure shows the variations of pay load with other elements for a series of airplanes similar in every respect except

* British Advisory Committee for Aeronautics, Reports and Memoranda No. 576.

in the particular feature under consideration. It will be noted that in Fig. 1 the assumption is made that only wing weights vary appreciably with size and factor of safety. While not strictly correct, the error is very slight.

In Figs. 2 and 4 single Liberty-engined airplanes have been considered, while in Figs. 3 and 5 those dealt with are twin Liberty-engined airplanes. Fig. 6 includes the two types. These machines may be regarded as typical of commercial airplanes. All corrections have already been made so that the net pay load can be read directly. The "theoretical number of passengers" scales are so marked because they indicate the number of passengers which the machine can actually lift. Other design considerations, particularly the size of the fuselage, may make it impracticable to accommodate the full number. In Fig. 11, later, the assumption is made that twelve passengers is the limit for a machine of about 420 HP and that this limit varies directly with the horsepower. This is somewhat arbitrary but is based upon experience and should be regarded as an ultimate limit. For ordinary practice, ten instead of twelve passengers should be taken as the present limit for this size of airplane.

Operating Cost.

Available data on the cost of operating commercial airplanes on a comprehensive scale are very limited and practically confined to the records of the U. S. Air Mail Service. The author's association with this organization as its consulting engineer some time ago gave him an opportunity to study it at close range and he

feels satisfied that it may be regarded in every way as a commercial air line. Incidentally, it is incontestably the largest commercial air line in the world. Careful and fairly complete records have been kept of the cost of operating this service and the figures which they give form the most trustworthy information at present available. The allowance which has been made for interest on investment is not complete. However, were it even doubled it would only increase the total cost 3.4 per cent, or, if trebled, 6.8 per cent, so the error is evidently within reasonable limits. It also appears reasonable to assume that this slight increase could be offset by certain economies possible under private operation.

The report of the Air Mail Service for the twelve months ending June 30, 1921, shows the average cost of operating its Liberty 420-HP-engined airplanes to have been \$71.13 per hour of flight.* Fig. 7 shows graphically the actual division of this cost over the various items. In estimating cost of operation, in the absence of other data, the assumption has been made that the Air Mail figure is a fair average for 420 HP machines and that it will vary directly with the engine horsepower.

Operating Cost vs. Duration.

We have heard some mention of operating airplanes through from New York to Chicago without an intermediate stop. This distance is about 700 miles in a straight line or 908 miles on the Pennsylvania Railroad. Along the course taken by an airplane it would be 750 to 800 miles owing to the impracticability of flying

*More recent data, which have become available since the study was made, show this figure to have decreased with continued operation.

in a dead, straight line. The great increase in cost of making this flight by eliminating the intermediate stop will be immediately evident from Fig. 8. This figure shows that the operating cost per pound-mile or passenger-mile increases gradually with the duration or distance up to about 4 or 5 hours or 432 to 540 miles. Beyond this the curve takes a rapid upward turn and the cost of operating machines of over 6 hours' duration becomes prohibitive.

If we assume a 420 HP airplane of the type described under the caption of Fig. 8, having 4 hours' duration and factor of safety of 6, the cost of operation becomes about 0.035 cent per pound-mile. Increasing this duration to 6 hours raises the cost to 0.049 cent or 40 per cent. Doubling the duration, to safely make the New York-Chicago flight without a stop, raises the operating cost to 0.086 cent per pound-mile, an increase of 146 per cent. The general conclusion to be drawn is that commercial airplanes of this size should not be designed for over 4 or 5 hours' duration. Considering now Fig. 9 for larger machines, this effect is more pronounced and it becomes advisable to keep the designed duration even below 4 hours, where possible.

Operating Cost vs. Factor of Safety.

The importance of keeping the factor of safety as low as the conditions warrant is also very evident. Considering Fig. 8 again and increasing from 6 to 8 the factor of safety of the 420 HP, 4-hour-duration machine, the operating cost rises from 0.035 to 0.041 cent per pound-mile or 17 per cent. With the larger machine

about the same increase takes place. However, the greater stability and lower maneuverability of the larger airplane permits some slight reduction of the factor of safety. In either case the necessity of keeping factors of safety within limits is apparent.

Operating Cost vs. Speed, Climb, and Reserve Horsepower.

The effects on operating cost of speed, climb, and reserve horsepower are considered together, as these factors are inseparable if the low or landing speed remains constant. As landing speed is usually fixed by ground conditions, etc., there appears to be no reason for considering these variations separately. Fig. 10 shows the variation of climb and cost with speed, power loading, and reserve horsepower for two series of freight airplanes. Speeds have been taken as at 5000 ft. altitude to provide a better comparison, as commercial flying will take place at altitudes close to this for safety reasons. With supercharged engines, however, higher altitudes will probably be used because of the higher speeds thus made obtainable.

Starting from the lower speeds the cost of operation rises steadily until about 105 or 110 m. p. h. is reached when a rapid upturn takes place, carrying this cost to prohibitive values for speeds above 110 or 115 m. p. h. The effect of factor of safety is also noticeable, particularly at the higher speeds. It is important to note here that of all the curves presented in this paper, Figs. 10 and 11 are the most susceptible to modification when applied to radically different types of design. At the same time

they may be taken to apply to present-day airplanes of good, conventional design. The only effect of extremely fine lines would be to raise slightly the critical speed at which the cost becomes prohibitive. Against this possibility of refinement must be balanced the fact that the large fuselages necessary for commercial work place a limit on the reduction of head resistance.

In determining the best operating speed a compromise must be effected between low speed with its low reserve horsepower and high speed with its high cost. At the top of fig. 10 a scale of reserve horsepower will be noted. This was obtained by plotting climb against power loading and extending the curve down to the point where climb became negligible. The speed at which this occurred was taken as the speed corresponding to the machine at the lower end of the series and having no reserve horsepower. The reserve horsepower scale was then laid off from the loading. This scale is approximate because, among other items, it does not take propeller efficiency into consideration. However, it is of value in furnishing a fair measure of what can be done with reduced engine speeds.

The necessity of keeping reserve horsepower down to reasonable limits is immediately evident. Experience has shown that an initial climbing speed of 400 to 500 ft. in the first minute is about the lowest consistent with safety, for operation from sea-level territory. To provide a basis for comparison an initial climb of 500 ft. in the first minute is assumed to be satisfactory. This gives a reserve horsepower of about 58 per cent and a high speed at 5000 ft. of 106 m.p.h. while the operating

cost for safety factor of 6 is 0.032 cent per pound-mile for a 420 HP machine or 0.034 cent per pound-mile for the 840 HP machine.

Flying on One out of Two Engines. Let us assume that the twin-engined machine is required to fly on one of its engines. Reserve propeller horsepower of at least 100 per cent must be provided. With only one engine running the lower speed will cause a drop in propeller efficiency from 80 per cent to about 70 or 75 per cent. Taking a propeller efficiency of 72.5 per cent, the reserve horsepower required becomes: $(80 \times 100) \div 72.5 = 110$ per cent. Consulting Fig. 10 we find that climb has increased to 980 ft. in the first minute, speed at 5000 ft. has increased to 130 m.p.h., and cost of operation to 0.089 cent per pound-mile. In other words, the machine under consideration has been taken right out of the commercial class and put into the military-fighter class, while its cost of operation has increased to 163 per cent over that of a rational commercial design.

Even assuming the possibility of maintaining efficiency at 80 per cent by using a variable-pitch propeller, the increase in operating cost is still 118 per cent over normal. A study of Fig. 11 will show that the same results are obtained with the passenger machines. These figures should be sufficient to demonstrate the utter impracticability of the requirement that twin-engined machines be designed to fly on one of their engines. It seems safe to say that the prohibitive operating cost resulting from enforcement of this requirement would be sufficient to elim-

to the possibility of developing commercial airplane transportation.

Flying on Two out of Three Engines. If a three-engined machine is required to fly on two of its engines a minimum reserve propeller horsepower of 50 per cent is necessary. Assuming drop in propeller efficiency from 80 per cent to 75 per cent the required reserve horsepower of the engine becomes: $(80 \times 50) \div 75 = 53.3$ per cent. This is about the reserve required to provide the climb necessary for safe operation. It is thus evident that the requirement of flying on two out of three engines is reasonable and practicable.

Aside from landing speed the one element of paramount importance in determining the safety of commercial aircraft is its climbing speed, this being a measure of reserve horsepower. As an initial climb rate of 400 to 500 ft. in the first minute has been found to be consistent with safety, no reason for increasing this is apparent. If, therefore, we are to write safety requirements for performance of commercial airplanes, the most logical measure to use would be their climbing speed.

Operating Cost vs. Size of Machine.

The curves of Fig. 12 are based upon calculations of machines of 250, 500, 1000, 2000 and 3000 sq.ft. wing area. Some arbitrary assumptions regarding the number of men in the respective crews were necessary and the numbers used have been given at the top of the graph.

The form of these curves was a surprise to the author, the economical sizes being much lower than he had anticipated. They show marked economy for machines of the type under consideration in the size in which the wing area is about 500 to 600 sq.ft. This economical size would, of course, be changed somewhat were the performance of the series altered. The quick upturn of the cost curves for small sizes of machines is due to the constant allowance for weight of the pilot crowding out a larger percentage of the net pay load. The slight "hump" in the same curves at about 1000 sq.ft. area is due to the allowance for a crew of two, while the gradual rise toward the larger machines is due to the increased structural weight of the wings and to the allowance of three men for the crew. This increase can be modified somewhat by further refinement in design but an allowance corresponding to existing practice has already been made. To avoid the very laborious work of estimating in detail the investment and operating cost for each size the following assumptions have been made: (1) That the Air Mail cost applied directly to the 420 HP, 630 sq.ft. size; and (2) that the operating cost for other sizes varied directly with the size. In considering the question of size, some preference should be given to machines having more than one pilot. The added safety thus obtained makes it worthwhile to sacrifice some possible savings by reducing size.

Operation Cost vs. Landing Speed.

No detailed study of the effect upon operating cost of varying the landing speed or low speed has been included. Landing

speed being practically fixed by the field conditions to be met, very little variation is permissible when the design is being made. Consequently it appeared unnecessary to go into this effect as thoroughly as into other features of performance.

Comparison with Railroad Cost.

A detailed and comprehensive comparison of airplane cost with railroad rates is not within the scope of this paper. However, one example is cited to emphasize the importance of the foregoing figures and to correct the impression that air transport is enormously expensive. The distance from New York to Chicago, as previously stated, is 908 miles on the Pennsylvania Railroad or about 700 miles in a straight line, a flying distance, say, of from 750 to 800 miles. Were it possible to load the airplane fully on each trip, the operating cost would be 6.5 cents per passenger-mile or \$48.75 to \$52 per passenger. This compares with the railroad rate of \$51.30, including fare, excess fare, and pullman. Allowing for the trip to and from the fields, as well as an intermediate stop, the time by air would average about 9 hours as against 20 hours by the Pennsylvania Railroad's "Broadway Limited." The only reason why we cannot carry passengers at such rates today is that it costs too much to get the business.

Conclusions.

The following general conclusions may be drawn from the data considered:

Duration. That designed duration should not exceed the min-

imum necessary to complete scheduled trips safely in a head wind and that, for the type considered, it should not in any case exceed four hours.

Factor of Safety. That the factor of safety should be kept to the minimum consistent with the conditions and that it should in no case exceed six.

High Speed. That high speeds beyond those accompanying the necessary reserve horsepower are undesirable and, for the type considered, the high speed should not exceed 105 to 110 m.p.h. at 5000 ft.

Climbing Speed. That climbing speed should be only sufficient to provide a reasonable margin of safety for emergencies, and an initial rate of climb of 400 to 500 ft. (from the altitude of the operating field) in the first minute is proposed as a tentative standard.

Reserve Horsepower. That reserve horsepower should be kept down to that necessary to provide the required climbing speed.

Flying on One out of Two Engines. That flying on one out of two engines is utterly impracticable, because of prohibitive cost.

Flying on Two out of Three Engines. That the requirement of ability to fly on two out of three engines is reasonable and practicable.

Safety Requirements. That initial rate of climb instead of reserve horsepower or speed range should be the measure of safe performance.

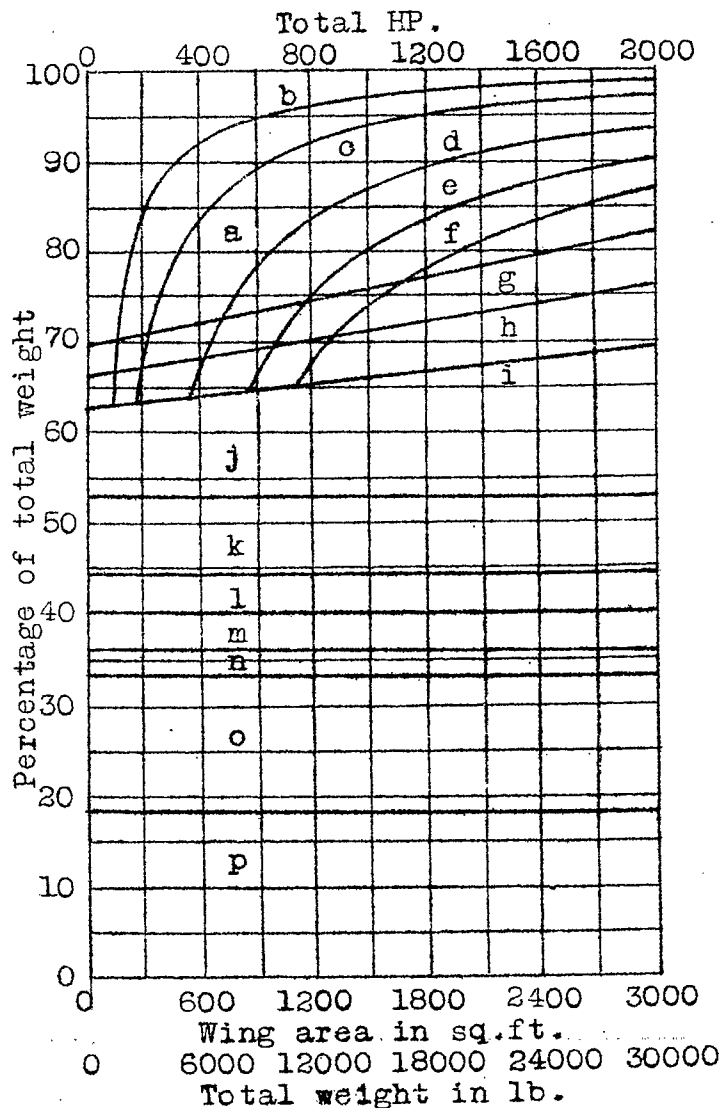
Size. That the moderate-sized machine is the most efficient at present, and for the type considered this size is about 500 to

600 sq. ft. in area.

Operating Cost. That aircraft designed for commercial purposes and fully loaded can be operated conservatively at a total cost of 0.030 to 0.032 cent per pound-mile or about 6.5 cents per passenger-mile, not including the cost of obtaining the business, and that this cost cannot be even approached by machines not suited to the purpose.

Archibald Black was born in Scotland but came to this country when eighteen years of age and was educated at Cooper Institute, Cass Technical Institute, and Columbia University. Until 1915 he was engaged in electrical construction and electrical engineering of power plants with several firms, including the New York Edison Co., the Detroit Edison Co., the Union Metallic Cartridge Co., and the Interborough Rapid Transit Co. He first became interested in aircraft work in 1910, and in 1915 entered the employ of the Curtiss Aeroplane Co., Buffalo. He was associated successively with the L-W-F Engineering Co., College Point, N.Y., the Bureau of Construction and Repair of the U.S. Navy, Washington, D.C., and the firm of A. & D. R. Black, consulting engineers of New York and Washington. He is now consulting engineer in Garden City, New York. Mr. Black was in charge of the design of the experimental airplane in which the first Liberty airplane engine was installed and was the designer of the L-W-F Model G, the first all-American fighting airplane.

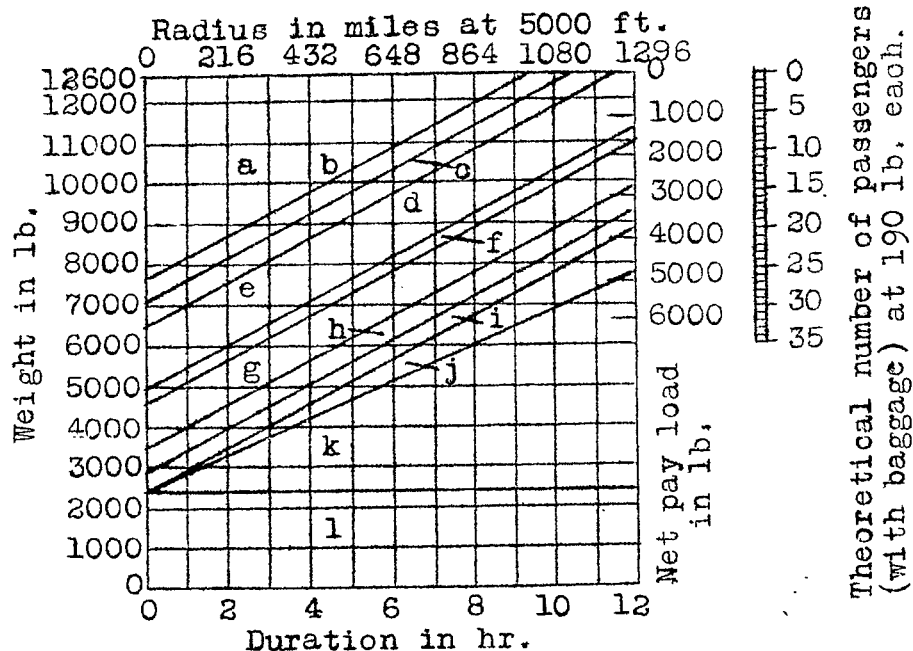
a-Crew, passengers and freight
 b-5000 lb.
 c-10000 lb.
 d-20000 lb.
 e-30000 lb.
 f-40000 lb.
 g-Safety factor 8
 h-Safety factor 6
 i-Safety factor 4
 j-Wing structure
 k-Front fuselage, engine supports, and controls
 l-Rear fuselage and tail unit
 m-Landing gear
 n-Tanks
 o-Gasoline and oil
 p-Engine, propeller, radiator and water



(For condition of 10 lb. per sq.ft., 15 lb. per HP., and 4 hr. duration. Curved lines represent conditions of constant useful load.)

Fig. 1 Division of weight of fully loaded airplanes.

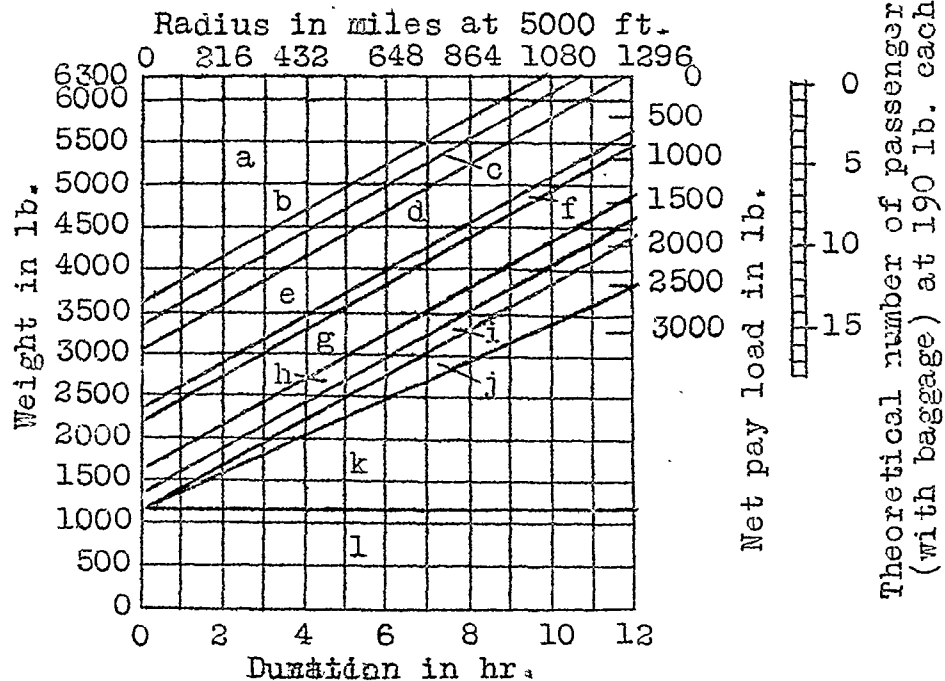
- a-Pay load
- b-Safety factor 8
- c-Safety factor 6
- d-Safety factor 4
- e-Wings
- f-Pilot and mechanic
- g-Front fuselage, etc.
- h-Rear fuselage and tail
- i-Landing gear
- j-Tanks
- k-Gasoline and oil
- l-Engine, propeller, radiator and water



(One 420-HP. Liberty engine; total weight 6300 lb.; wing area, 630 sq.ft.; high speed, 108 M.P.H. at 5000 ft.; minimum speed 57 M.P.H.-10 lb.per sq.ft.; climb from sea level, 565 ft. first min.)

Fig. 2 Variation of weight division with duration, 420-HP. airplane

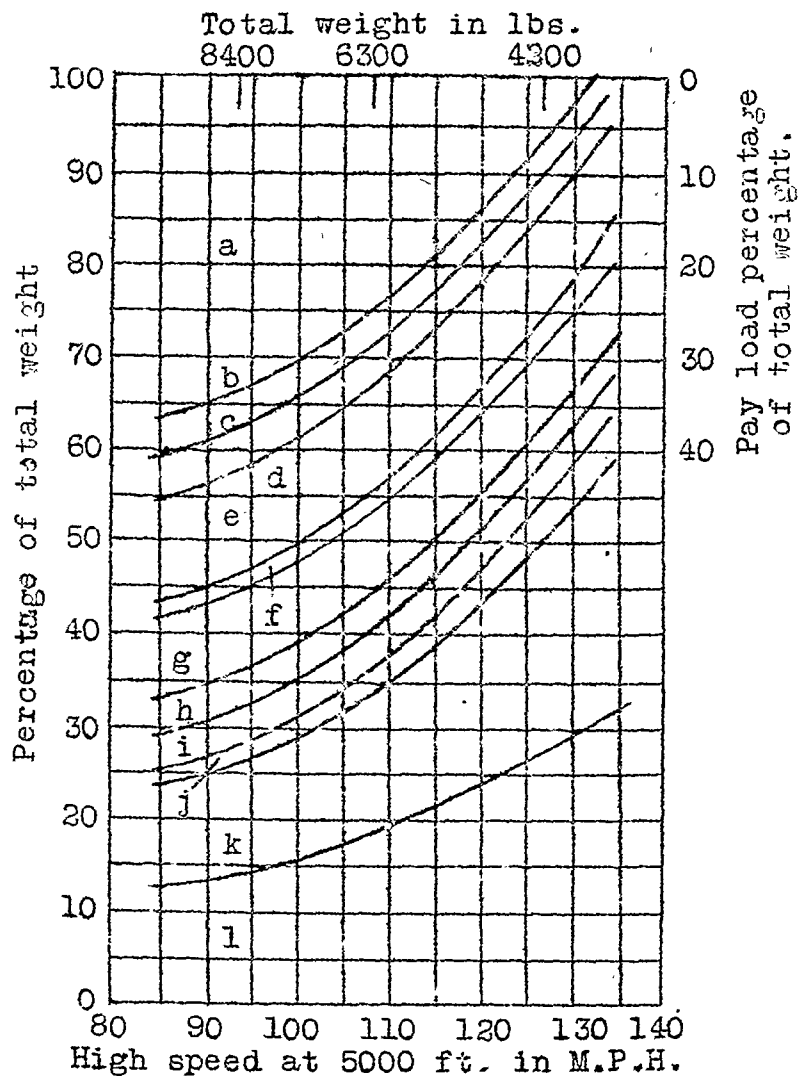
- a-Pay load
- b-Safety factor 8
- c-Safety factor 6
- d-Safety factor 4
- e-Wings
- f-Pilot
- g-Front fuselage, etc.
- h-Rear fuselage and tail
- i-Landing gear
- j-Tanks
- k-Gasoline and oil
- l-Engine, propeller, radiator and water



(Two 420-HP. Liberty engines, 840-HP.; total weight 12600 lb.; wing area, 1260 sq.ft.; high speed 168 M.P.H. at 5000 ft.; minimum speed, 57 M.P.H.-10 lb. per sq.ft.; climb from sea level, 565 ft. in first min.)

Fig. 3 Variation of weight division with duration, 840-HP. airplane.

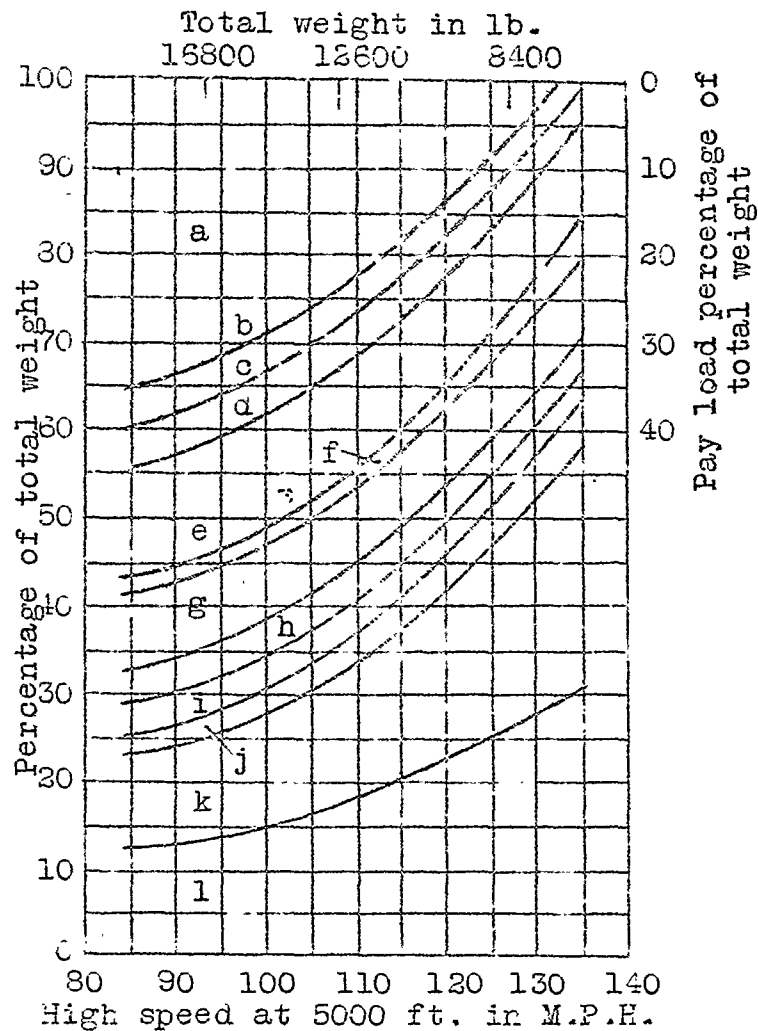
a-Pay load
 b-Safety factor 8
 c-Safety factor 6
 d-Safety factor 4
 e-Wings
 f-Pilot
 g-Front fuselage, etc.
 h-Rear fuselage and tail
 i-Landing gear
 j-Tanks
 k-Casoline and oil
 l-Engine, propeller, radiator and water



(Liberty engine, constant minimum speed, 57 M.P.H.; duration, 4 hr.; wing loading 10 lb. per sq.ft.)

Fig. 4 Variation of weight division with speed-420 HP. Airplane.

- a-Pay load
- b-Safety factor 8
- c-Safety factor 6
- d-Safety factor 4
- e-Wings
- f-Pilot and mechanic
- g-Front fuselage, etc.
- h-Rear fuselage and tail
- i-Landing gear
- j-Tanks
- k-Gasoline and oil
- l-Engine, propeller, radiator and water



(Two Liberty engines, constant minimum speed, 57 M.P.H.; duration, 4 hr.; wing loading, 10 lb. per sq.ft.)

Fig. 5 Variation of weight division with speed
840-HP. airplane

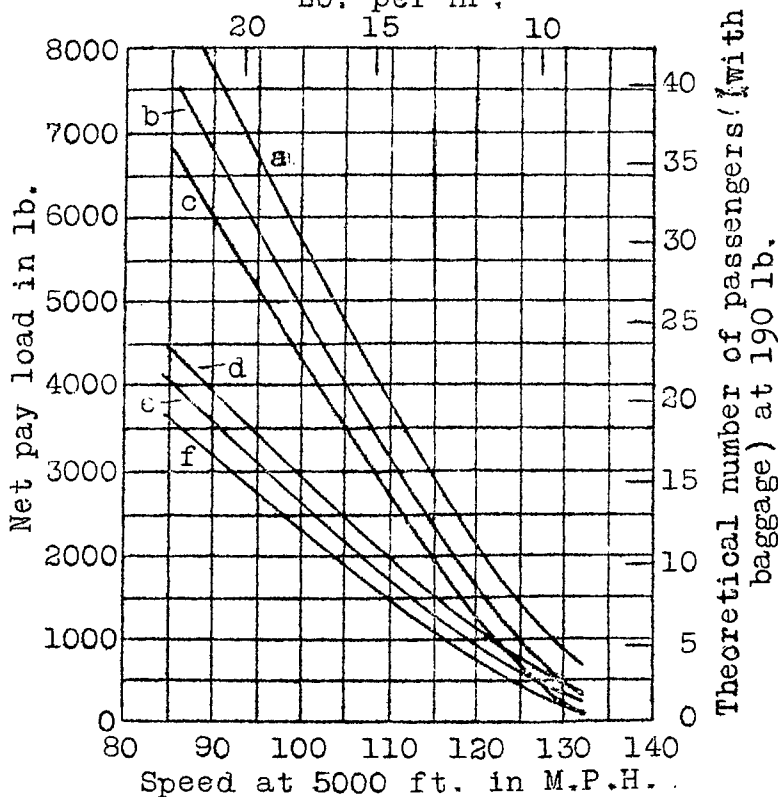
- a-Twin engined (840 HP.) Safety factor=4
- b-Twin engined (840 HP.) Safety factor=6
- c-Twin engined (840 HP.) Safety factor=8
- d-Single engined (420 HP.) Safety factor=4
- e-Single engined (420 HP.) Safety factor=6
- f-Single engined (420 HP.) Safety factor=8

Feet climb in first min. (sea level)

265 565 1275

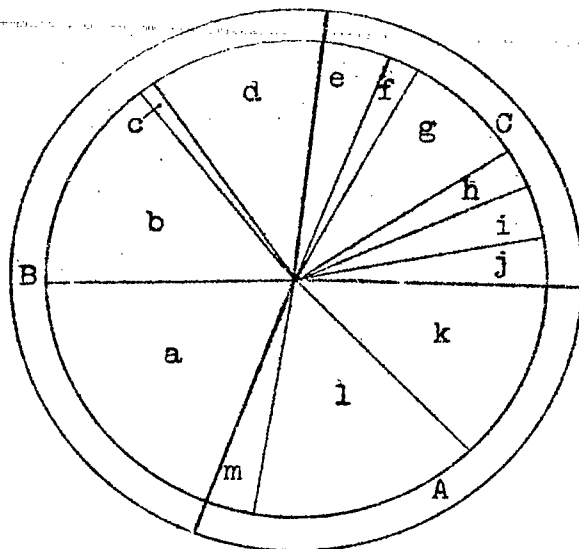
Lb. per HP.

20 15 10



(Series of single and twin Liberty engined airplanes, constant minimum speed 57 M.P.H.; duration, 4 hr.; wing loading, 10 lb. per sq.ft.)

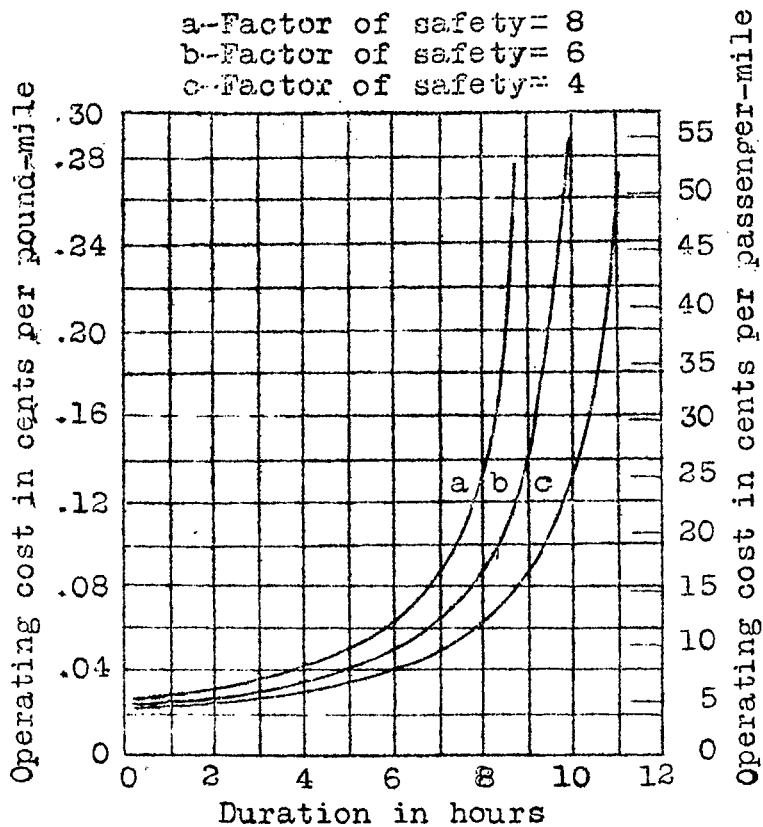
Fig. 6 Variation of net pay load with speed.



(U.S. Air Mail Service for twelve months ending June 30, 1921.)

- A-Flying, 30.58 per cent
- B-Maintenance, 45.76 per cent
- C-Overhead, 23.66 per cent
- a-repairs and accessories
- b-Mechanics and helpers
- c-Warehouse
- d-Miscellaneous
- e-Motorcycles and trucks
- f-Rent, light, fuel, power, phone, and water
- g-Office force and watchmen
- h-Radio
- i-Dept. overhead
- j-Interest on investment
- k-Pilots
- l-Gasoline
- m-Grease and oil

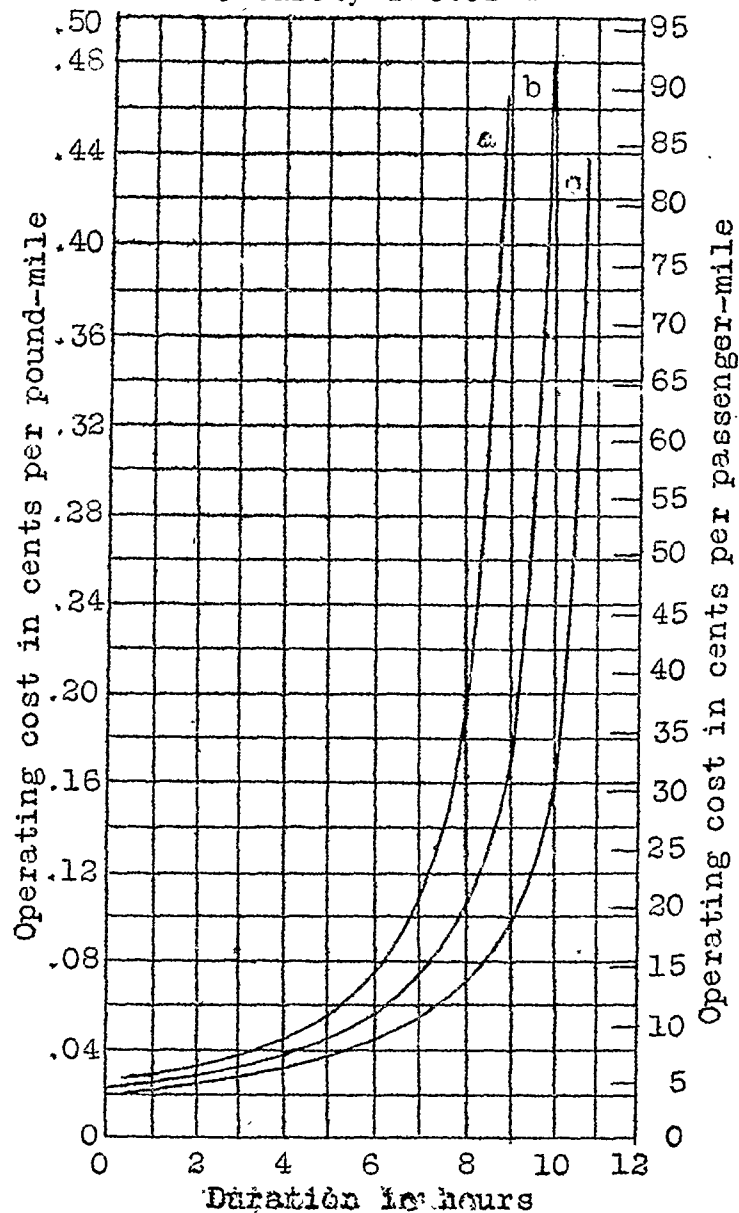
Fig. 7 Division of the operating dollar



(One 420-HP. Liberty engine; total weight, 6300 lb.; wing area, 630 sq.ft.; high speed, 108 m.p.h. at 5000 ft.; minimum speed, 57 m.p.h.; 10 lb. per sq.ft.; climb from sea level, 565 ft. in first minute.)

Fig. 8 Variation of cost with duration-420-HP Airplane

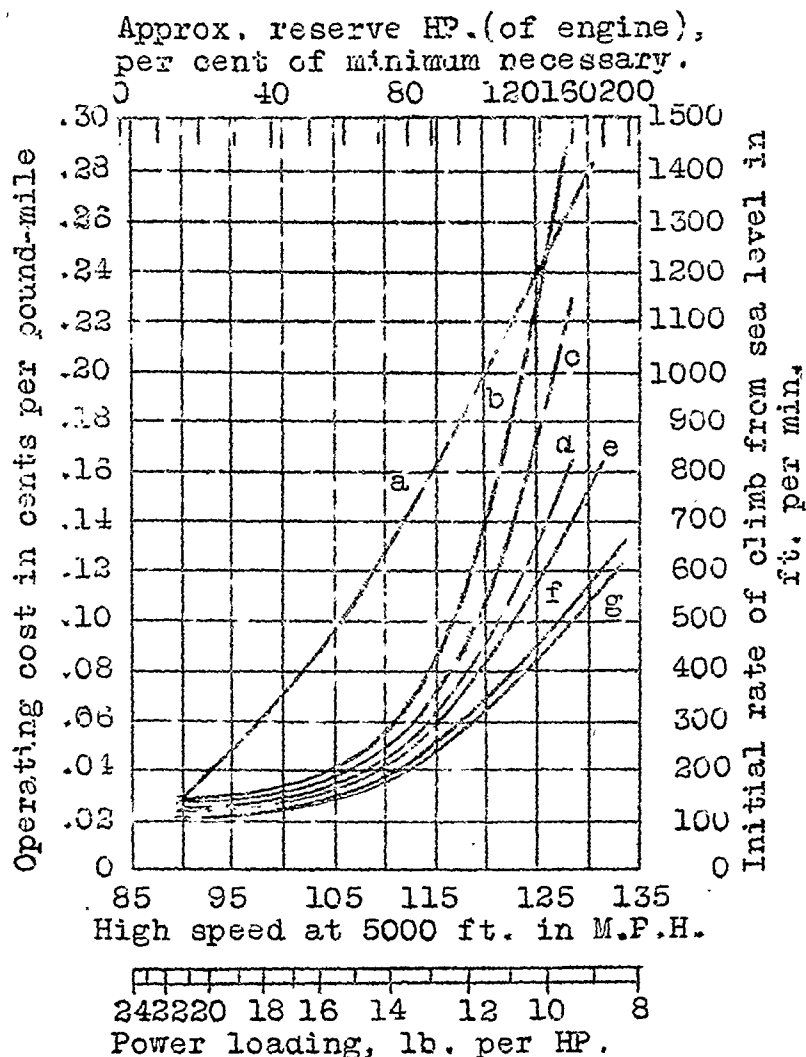
a-Safety factor=8
b-Safety factor=6
c-Safety factor=4



(Two 420 HP. Liberty engines, 840 HP.; total weight, 12,600 lb.; wing area, 1260 sq.ft.; high speed, 108 M.P.H. at 5000 ft.; minimum speed, 57 M.P.H.-10 lb. per sq.ft.; climb from sea level, 565 ft. in first min.)

Fig. 9 Variation of cost with duration-840 HP. Airplane.

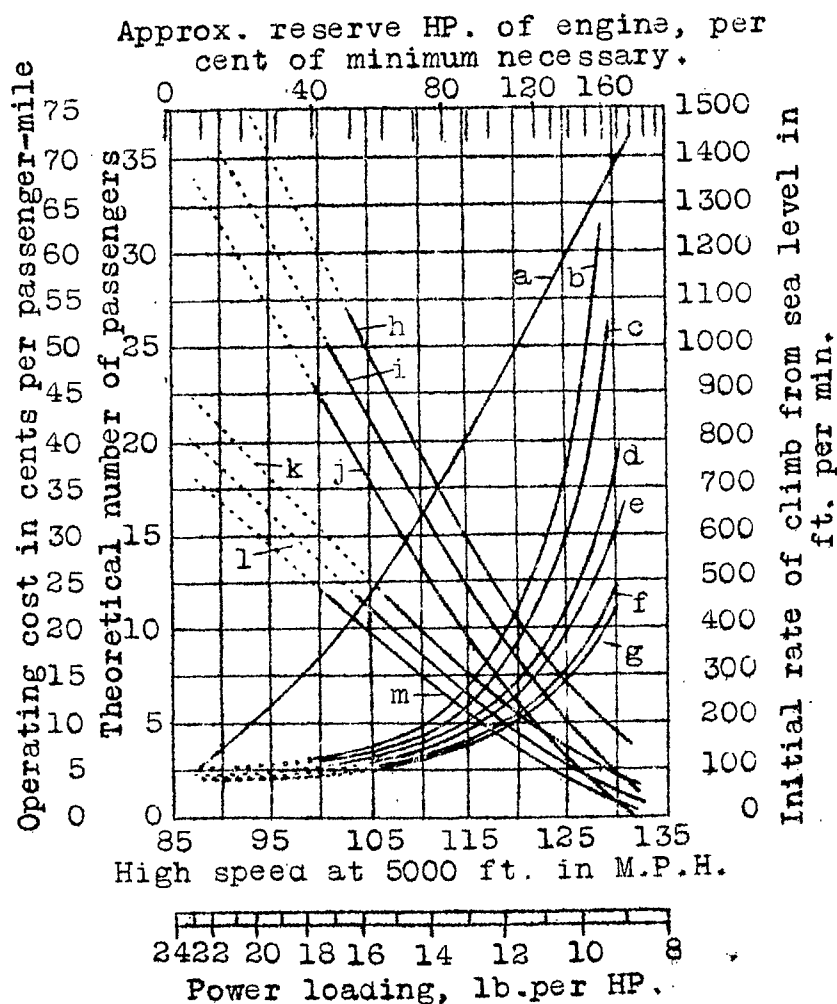
- a-Initial rate of climb
- b-Cost (twin engine) Safety factor 8
- c-Cost (single engine) Safety factor 8
- d-Cost (twin engine) Safety factor 6
- e-Cost (single engine) Safety factor 6
- f-Cost (twin engine) Safety factor 4
- g-Cost (single engine) Safety factor 4



(Series of single and twin Liberty engine freight airplanes of constant minimum speed of 57 M.P.H.-10 lb. per sq.ft.; duration, 4 hr.)

Fig. 10 Variation of cost and climb with speed and reserve HP.

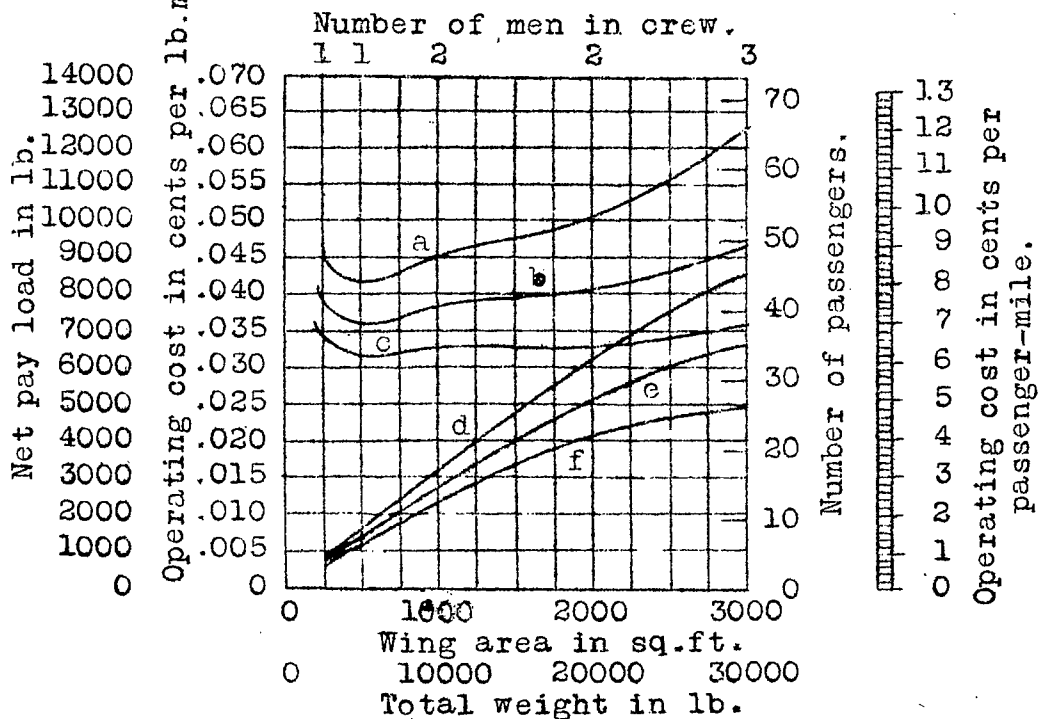
- a-Initial rate of climb
- b-Cost (twin engine) Safety factor 8
- c-Cost (single engine) Safety factor 8
- d-Cost (twin engine) Safety engine 6
- e-Cost (single engine) Safety factor 6
- f-Cost (twin engine) Safety factor 4
- g-Cost (single engine) Safety factor 4
- h-Passengers (twin engine) Safety factor 4
- i-Passengers (twin engine) Safety factor 6
- j-Passengers (twin engine) Safety factor 8
- k-Passengers (single engine) Safety factor 4
- l-Passengers (single engine) Safety factor 6
- m-Passengers (single engine) Safety factor 8



(Series of single and twin Liberty engined passenger airplanes, constant minimum speed, 57 M.P.H.-10 lb. per sq.ft.; duration, 4 hr. Dotted curves indicate capacity above practical limit. Passengers calculated at 190 lb. each including baggage.)

Fig. 11 Variation of cost, climb and passengers with speed and reserve HP.

- a-Cost for safety factor 3
- b-Cost for safety factor 6
- c-Cost for safety factor 4
- d-Pay load and passengers, Safety factor 4
- e-Pay load and passengers, Safety factor 6
- f-Pay load and passengers, Safety factor 3



(Series of airplanes loaded 10 lb. per sq.ft.; 15 lb. per HP.; duration, 4 hr.; minimum speed 57 M.P.H.; high speed, 108 M.P.H. at 5000 ft.; climb from sea level 565 ft. in first min. Passengers calculated at 190 lb. each including baggage.)

Fig. 12 Variation of cost, pay load, and passengers with size.

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